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Motion of Minimal Configurations of a Modular Robot: Sinusoidal, Lateral Rolling and Lateral Shift

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Abstract

Complex modular robots can be constructed by means of simple modules. There is no geometric superior size to the total number of modules that can be added. The number of possible configurations growth exponentially. However, an inferior limit exists: the minimum number of modules needed to achieve the locomotion. In this paper, three minimal configurations has been developed using only two and three one-degree-of-freedom modules. The simplest one is pitch-pitch configuration, composed of two modules, which can move in a straight line, forward or backward, at different speeds. The second one is the pitch-yaw-pitch , with one more module that moves in the yaw axis. In this case, three new kinds of motion can be achieved: 2D sinusoidal motion, lateral shift and lateral rolling. Finally, the third configuration is a three-modules star, that can be moved in three directions as well as rotated parallel to the ground.

Keywords: Modular, gaits, rolling.

1 Introduction

Modular robots are composed of simple modules[1]. Different robot configurations, like snakes or spiders, can be constructed by linking modules. Some robots are self-reconfigurable and capable of changing its shape, like Polybot[2]. The number of robot following this approach has increased substantially [3][4][5]. The main advantages are versatility, robustness and low cost. Applications outside the research world has not been seen yet,

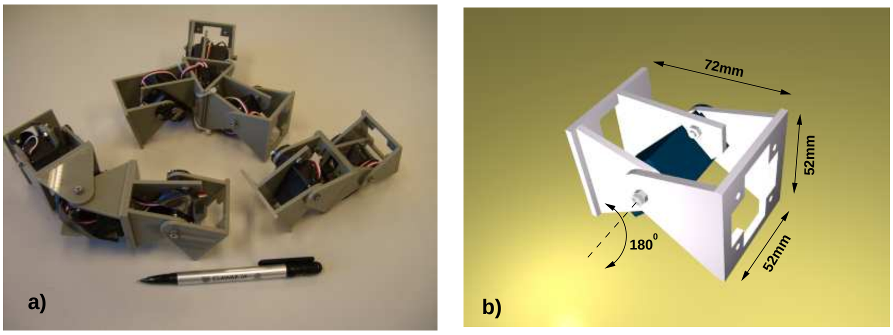

Fig. 1. a) The three modular configurations constructed, composed of two and three Y1 modules: Pitch-Pitch (PP), Pitch-Yaw-Pitch (PYP) and three-modules star. **b)** A cad rendering of the Y1 modules

but they are planned to be used in space applications[7] and urban search and rescue[6].

The amount of different configurations growth exponentially with the number of modules and there is no geometrical limitation to the total number of modules. In this paper we focuses on the minimum number of modules needed to achieve locomotion and to perform motions like lateral rolling[8] and lateral shift. Also, the study of motion of these minimal configurations is developed for a better understanding of the locomotion's properties of more complex configurations.

Three modular robots using one-degree-of-freedom modules are presented (**Fig.1a**). The simplest one has only two modules and it is capable of moving forward and backward. Adding just one more module, three new types of locomotion appears: 2D sinusoidal locomotion, lateral rolling and lateral shift.

2 Construction of the modular configurations

The three configurations developed are based on the Y1 modules (**Fig.1b**), designed for the Cube worm-like robot[9]. The rotation range is 180^0 and the dimensions are 72x52x52 mm, as shown in **Fig.1b**. These modules are inspired in Polybot G1, designed by Mark Yim at PARC.

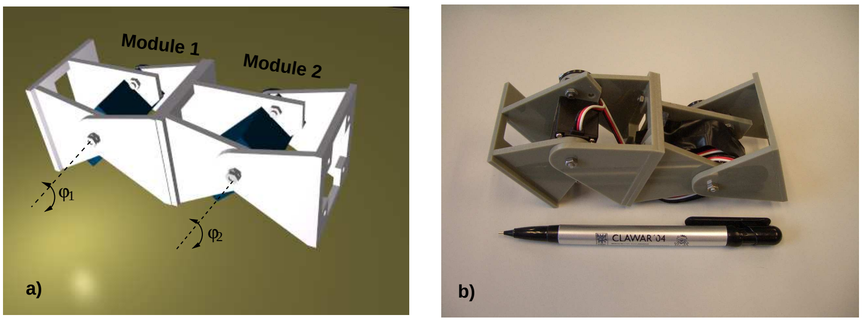

Fig. 2. Pitch-Pitch (PP) configuration, composed of two Y1 modules connected in the same orientation.

3 Configuration 1: Pitch-Pitch (PP)

This configuration is constructed attaching two Y1 modules as shown in **Fig.2**. Experiments show that this configuration can move on a straight line, backward and forward. Also, the velocity can be controlled. Therefore, this is the minimal possible configuration for locomotion, using this modules.

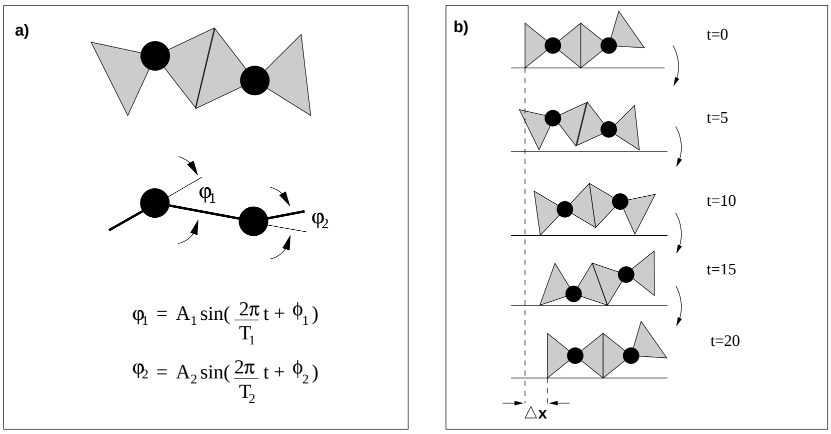

Fig. 3. a) PP configuration parameters and control. **b)** Locomotion of the PP configuration when $A = 40^0$, $\triangle\phi = 120$ and $T = 20$.

Fig.3a shows the robot parameters. φ_1 and $\varphi_2$are the rotation angles of the modules 1 and 2 respectively. The locomotion is achieved by applying a sinusoidal function to the rotation angles:

$$\varphi_i = A_i \sin\left(\frac{2\pi}{T_i}t + \phi_i\right) \qquad (1)$$

where $i \in \{1, 2\}$. The values of the parameters: A_i, T_i and ϕ_i determines the properties of the movement.

In order to simplify the experiments, the following restrictions have been applied: $A_1 = A_2 = A$, $T_1 = T_2 = T$, therefore, φ_1 and φ_2 are the same sinusoidal function with a different phase ($\triangle\phi = \varphi_2 - \varphi_1$). The period has been fixed to 20 unit of time.

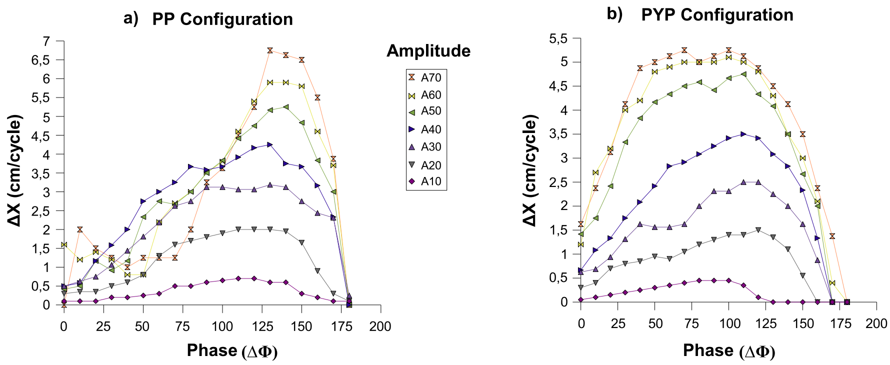

Fig. 4. The distance per cycle roved ($\triangle x$) as a function of the phase and amplitude. **a)** Pitch-Pitch configuration. **b)** Pitch-Yaw-Pitch configuration with $\varphi_2 = 0$

The motion is cyclical, with a period of T. After T unit of time, the movement is repeated. The space per cycle roved by the robot is $\triangle x$. **Fig.4a** shows the relation between $\triangle x$ and the phase ($\triangle\phi$) and amplitude (A) of the waves applied. As can be seen, $\triangle x$ increases with the increment of amplitude. Therefore, the speed of the locomotion can be controlled by the amplitude of the wave.

The difference in phase determines the coordination between the two articulations. If the modules rotates in phase($\triangle\phi = 0$), no locomotion is achieved. The same happens when $\triangle\phi = 180^0$. The best coordination is obtained when $\triangle\phi \in [110, 150]$. For negative values ($\triangle\phi \in [0, -180]$), the locomotion is done in the opposite way.

Fig.3b shows the position of the articulations at five instants, when $A = 40^0$,$\triangle\phi = 120$ and $T = 20$.

4 Configuration 2: Pitch-Yaw-Pitch (PYP)

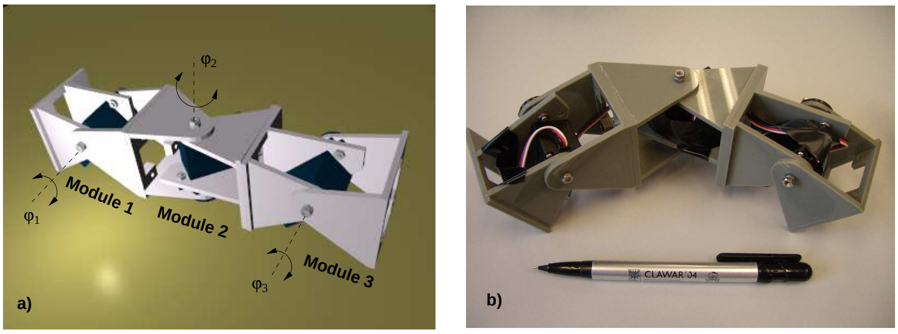

Fig. 5. Pitch-Yaw-Pitch (PYP) Configuration. **a)** A cad rendering showing the three modules and its rotation angle ranges. The module angles φ_1, φ_2 and φ_3 are set to 0. **b)** A picture of the robot

Three Y1 modules are employed in this configuration. The outermost modules rotate in the pitch axis and the one at the center in the yaw axis (**Fig.5**). Only one more module is added, but three new kind of gaits can be realized: 2D sinusoidal movement, lateral rolling and lateral shift. The same sinusoidal function is applied (equation 1) but in this case $i \in \{1, 2, 3\}$.

4.1 1D Sinusoidal motion

When φ_2 is fixed to 0, this configuration has the same shape as in **Fig.5a** and therefore, it is very similar to PP configuration. It only can move on a straight line, forward and backward. The experimental results are shown in **Fig.4b**. The velocity of the movement increases with the amplitude and there is a phase window in which the coordination is better. For the same amplitude, the space roved is less than in PP configuration but the phase window is wider. As the distance between the outermost modules is greater than in PP configuration, it is most difficult for this two modules to carry out the locomotion. Therefore the $\triangle x$ is smaller.

4.2 2D sinusoidal motion

If φ_2 is between 0^o and 40^o, the locomotion has the same characteristics than in the previous case, but the movement is not a straight line: The robot trajectory is an arc. The constraints used in this movement are: $A_1 = A_3 = A$, $T_1 = T_3 = T$, $\varphi_2 \in [0, 40]$.

4.3 Lateral Shift

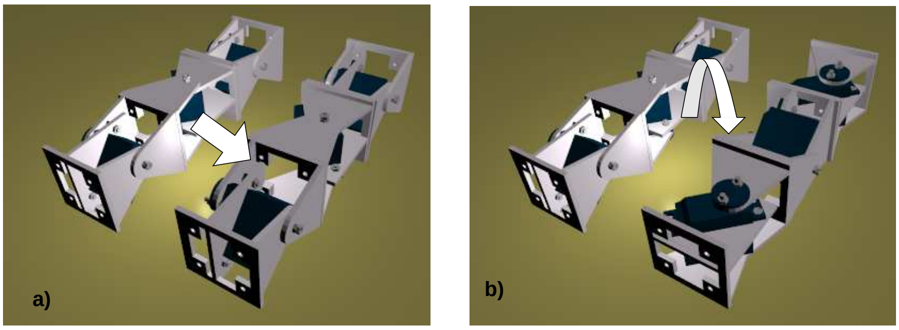

Fig. 6. a) Lateral shift gait in PYP configuration. **b)** Lateral rolling gait in PYP configuration

PYP configuration can move using a lateral shift gait. It moves parallel to itself, as shown in **Fig.6**. Three sinusoidal waves are applied to all the modules with the following restrictions: $A_1 = A_2 = A_3 \in (0, 50)$, $T_1 = T_2 = T_3$, $\phi_1 = \phi_3 = 0$, $\phi_2 = 90$. The amplitude of the waves are the same, with a value greater than 0 and smaller than 50.

4.4 Lateral Rolling

PYP also can perform a lateral rolling gait (**Fig.6**b). The restrictions are the same as in lateral shift but the amplitude of the waves are greater or equal than 60: $A_1 = A_2 = A_3 >= 60$.

When PYP rolls 90^o it is converted into a YPY (yaw-pitch-yaw) configuration. Now, it only has one module on the pitch axis. Therefore, it cannot move forward or backward. But lateral shift or lateral rolling can still be achieved. When lateral rolling is performed, configurations PYP and YPY appears alternatively.

5 Configuration 3: Three-modules star

The last configuration tested was a three-modules star, shown in **Fig.7**. The modules form a star of three points with an angular distance of 120^0.

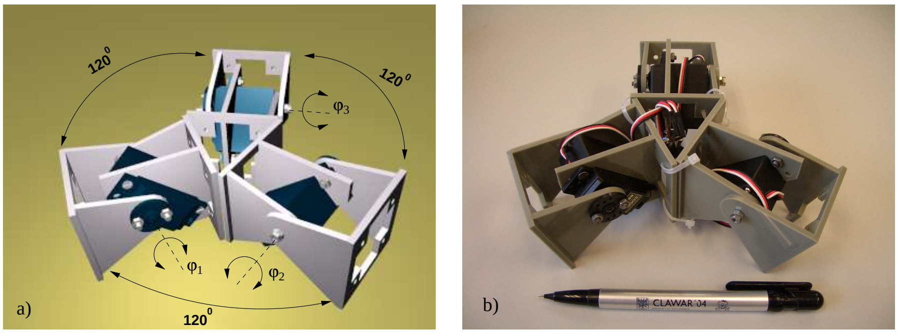

Fig. 7. The three-modules star configuration.

It can move on a 2D surface, in three directions, as well as performing rotations in the yaw axis. If two adjacent modules are in phase and the opposite has $\triangle\phi \in [100, 150]$, it moves on a straight in the direction of the module out of phase. However, this movement is very surface-dependant.

When the increment of phase between the three modules is 120^o, for example, $\phi_1 = 0$, $\phi_2 = 120^o$ and $\phi_3 = 240^o$, the robot performs a slow rotation in the yaw axis.

6 Conclusion and further work

Three different minimal modular configurations has been tested. Using only two modules, sinusoidal locomotion in straight line can be achieved. The difference of phase ($\triangle\phi$) between the two signal determines the coordination. The speed is controlled modifying the amplitude of the sinusoidal wave.

When adding one more module in the yaw axis, three new gaits can be performed: 2D sinusoidal motion, lateral rolling and lateral shift. All of them are realized using sinusoidal waves, changing the amplitude and phase.

Lateral shift and rolling differs only on the amplitude range. When all the amplitudes are below 40, a lateral shift motion is performed. If a value greater or equal to 60 is applied, lateral rolling is achieved.

In future works, new configuration will be constructed and tested, looking for simple coordination methods. Also, genetic algorithm will be used for the calculation of the optimal parameters (amplitude, phase) of these minimal configurations.

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